DEVELOPMENT OF A HUMIDIFICATION SYSTEM FOR USE IN FIELD STUDIES OF AIR POLLUTION EFFECTS ON CROPS

C. Ray Thompson
Principal Investigator

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Statewide Air Pollution Research Center
University of California
Riverside, California 92521

ABSTRACT

The primary objective of this work was to design and build a system which would provide definite, measurable levels of relative humidity in air over test plants so that the effects of this environmental condition could be measured on the response of plants to air pollutants, primarily ambient ozone.

A humidity generation system was designed, constructed, and tested for use in increasing relative humidity within open-top chambers under field conditions. The system consisted of a gas fired steam boiler capable of generating 450 kg of steam at 1.055 kg/cm^2 (15 PSI) pressure. This steam source was connected to two manifolds which supplied humidified air to two chambers. A modulating valve, controlled by a humidity sensor, metered steam to the chambers. Two ambient humidity chambers were used for comparison. One, each, of the humidified chambers received carbon filtered air, the other ambient air. The ambient humidity chambers also received filtered or ambient air.

Performance tests of the humidity generation system showed that with air temperatures of 30°C and ambient relative humidity of 10% the air humidity could be increased by 60%. At higher ambient humidities a greater maximum chamber humidity was achieved. Injection of steam into the ambient air chamber reduced ozone levels by about one fourth.

Alfalfa plants were exposed to 0.20 ppm ozone for seven hrs/day for two days to determine "acute" effects of ozone with different humidities. Neither growth nor number of nodes were affected by the short exposure but visible injury occurred on more than 50% of the leaves which had the high humidity and leaf drop was increased very significantly.

"Chronic" exposures of three cultivars of alfalfa to ambient ozone at ambient humidity or increased humidity occurred for three successive periods with harvests on April 25, May 16 and June 13, 1986. At the first harvest, visible injury occurred on 40% of the leaves exposed to ambient ozone with increased humidity. No statistically significant effects on plant growth occurred because ambient ozone was low during this period. Humidifying the air in general increased plant growth. The second harvest showed similar results. Stomatal conductance was measured and showed that humidification increases conductance, thus allowing greater gas uptake and

consequently greater injury to the plant by pollutants. The third harvest showed that the dry weight of alfalfa was reduced significantly by ambient ozone with high humidity. Defoliation due to ozone was increased significantly with added humidity.

This work showed that the basic engineering and design of the humidification system was sound, reliable, and workable. The facility will serve to obtain reliable information concerning the effects of relative humidity on crop losses from air pollutants.

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DISCLAIMER

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SUMMARY AND CONCLUSIONS

The primary objective of this work was to design and build a system which would provide definite, measurable levels of relative humidity in air over test plants so that the effects of this environmental condition could be measured on the response of plants to air pollutants, primarily oxidants. A humidity generation system was designed, constructed, and tested for use in increasing relative humidity within open-top chambers under field conditions. The system consisted of a gas fired steam boiler capable of generating 1.055 kg/cm^2 (15 PSI) of steam. This steam source was connected to two manifolds which supplied humidified air to two California Air Resources Board (CARB) chambers. A modulating valve, controlled by a humidity sensor, metered steam to the chambers. Two ambient humidity chambers were used for comparison. One, each, of the humidified chambers received carbon filtered air, the other ambient air. The ambient humidity chambers also received filtered or ambient air.

Performance tests of the humidity generation system showed that with air temperatures of 30°C and ambient relative humidity of 10% the air humidity could be increased by 60%. At higher ambient humidities a greater maximum chamber humidity was achieved.

Clones from three alfalfa cultivars, Mesa Sirsa and Moapa (both sensitive to ozone) and Northrup King 286 (resistant to ozone) were exposed in pots within the open-top chambers. Ozone was added at 0.20 ppm for seven hrs/day for two days to determine "acute" effects of ozone with different humidities. Neither growth nor number of nodes were affected by the short exposure, but visible injury occurred on more than 50% of the leaves which had the high humidity, and leaf drop was increased very significantly.

"Chronic" exposures of three cultivars of alfalfa to ambient ozone or filtered air at ambient humidity or increased humidity occurred for three successive harvests. At the first harvest, there was s significant interaction between ozone and leaf injury, with the most injury on leaves exposed to ambient oxidant and increased humidity. There were no statistically significant effects from ozone on plant growth because ambient concentrations were low during this period. Humidifying the air in general increased plant growth. The second harvest of alfalfa showed

similar results. Stomatal conductance also was measured during the second exposure, and showed that humidification increases conductance, thus allowing greater gas uptake and consequently greater injury to the plant by pollutants. The third alfalfa harvest showed that the dry weight of Moapa was reduced significantly by ambient ozone with high humidity. Defoliation due to ozone was increased significantly with added humidity.

The experimental results with the three harvests of the three cultivars of alfalfa show clearly that increasing the relative humidity allows the plants to grow faster but also renders them more susceptible to oxidants. The increased visible leaf injury followed by defoliation, and the increased stomatal conductance explains to some extent why the increased humidity results in greater injury yield losses.

One unexpected result was a reduction in ozone concentration when latent steam was injected into the CARB chamber. This effect has not been observed previously and further study is needed to elucidate the cause or mechanism. This effect would not affect future studies because an ozone source at the CARB facility is available to compensate for this effect.

Conclusions

(1) This work shows that the basic engineering and design of the humidification system is sound, reliable, and workable.

(2) The experimental results with the three harvests of the three cultivars of alfalfa show clearly that increasing the relative humidity allows the plants to grow faster but also renders them more susceptible to air pollutants.

(3) The increased visible leaf injury followed by defoliation, and the increased stomatal conductance in humidified chambers explain to some extent why the increased humidity results in greater yield losses from ozone.

(4) Better, more definitive, results are anticipated with this experimental system during late summer and early fall because the ambient humidity levels in Riverside are lowest during these periods thus allowing a greater difference in humidity levels between ambient and humidified atmospheres.

(5) The use of alfalfa as a test plant is very convenient because it can be harvested repeatedly thus giving a number of determinations of given effects as seasonal changes occur and because it grows so rapidly environmental effects become apparent quickly.

(6) The humidification facility can be used to estimate the effects of disparity in relative humidity levels between different regions of California on estimates of crop loss due to air pollutants.

RECOMMENDATIONS

The pilot humidification system performed well and demonstrated the feasibility of more complex humidity x pollutant interaction studies. Recommendations for field studies are:

(1) Conduct a late summer study (August through October), investigating the interaction of ambient ozone and humidity on crops. The study would emphasize the physiological basis, e.g., stomatal conductance and/or plant growth habit, for the interaction.

(2) Conduct a winter study (November through January), investigating the interaction of winter air pollutants; e.g., sulfur dioxide or peroxyacetyl nitrate (PAN) and humidity on crops. The study would emphasize the physiological basis for the interaction. Multiple crops would be tested.

(3) Conduct a spring study (March through May), investigating the interaction of ambient ozone and humidity on tree seedlings. The study would emphasize the physiological basis for the interaction. Multiple tree species would be tested.

These field studies would be accompanied by further development and testing of the field humidification system. The following will be considered:

(4) Increase the number of humidified chambers from two to six, thereby expanding the capacity of the system to provide for more treatment levels and/or replication of treatments.

(5) Develop the capability for computer feedback control of the humidification levels.

(6) Further investigate the ozone depletion problem with humidity addition.

I. INTRODUCTION

Relative humidity, i.e., the water vapor content of air, has long been considered to be an important factor in determining the air pollutant sensitivity of plants. In general, stomata of plants are more open when grown under conditions of high compared to low humidity (4,7,8,10,11,12). Open stomata allow an increase in the amount of air pollutants taken up by the leaves, thus increasing the amounts of toxic pollutant metabolites at the cellular level (7,8,9,10). At low humidities a relatively greater amount of water is lost from leaves via transpiration than at high humidities, thus limiting pollutant uptake, by inhibiting the mass flow of pollutants into leaves and adsorption of pollutants to leaf cells (2). The cumulative effect of these metabolic changes is a large (50-100%) decrease in leaf injury with a decrease in humidity from approximately 80 to 30% (4).

Humidity has been suggested as one of the most important factors determining the relative pollutant sensitivity of crops growing in different climatic areas of the country. McLaughlin and Taylor (9) hypothesized that perhaps different regional air quality standards should be designed to protect vegetation considering variations in regional environmental conditions, especially in regard to humidity. Such standards would allow higher pollutant concentrations in low humidity areas such as the southwestern United States than in high humidity areas such as the humid east.

However, not all variation in humidity is national in scope. Differences in humidity can occur between geographical areas of a state such as the Central Valley vs. the South Coast Air Basin of California (5) or between coastal areas and inland desert (Table 1). Differences in humidity can also be seasonal such as winter and spring versus summer or fall. Also, coastal areas such as near Oxnard have a higher relative humidity level than the Central Valley, or Southern Inland areas throughout the year. In addition, coastal areas have a relatively uniform humidity level throughout the day while Central Valley areas have a higher humidity level in mornings than afternoons during all parts of the year.

Humidity differences also occur on a local level, especially between fields with a dense canopy of crop foliage versus dry open areas. In 1983 an ozone episode had a devastating effect on dry bean cultivars the day

Table 1. Average Monthly Relative Humidity Levels at Different Times During the Day for Selected Cities[a]

City	Month	March			May			July			September		
	Time[b]	1000	1300	1600	1000	1300	1600	1000	1300	1600	1000	1300	1600
Central Valley													
Bakersfield		57	--[c]	42	38	--	25	32	--	20	41	--	27
Fresno		64	47	46	42	33	25	38	26	22	45	31	28
Red Bluff		57	--	44	40	--	28	30	--	19	34	--	22
Sacramento		68	--	52	51	--	36	47	--	28	51	--	31
Coast													
Oxnard		--	56	--	--	58	--	--	62	--	--	59	--
Salinas		--	59	--	--	65	--	--	69	--	--	64	--
San Diego		60	--	59	64	--	64	69	--	66	66	--	65
Santa Maria		63	--	64	62	--	61	64	--	61	63	--	62
Southern Inland													
Riverside		--	42	--	--	39	--	--	28	--	--	30	--

[a]From J. D. Goodridge, California State Climatologist, in Report Relative Humidity Measurements for California, (5).
[b]Time of measurement differs for the cities as the 1300 measurements are from U. S. Air Force bases and the other times are from airport data.
[c]The "--" indicates that relative humidity data was not collected at this time.

after a furrow irrigation (6). Earlier ozone episodes when the soil was dry did not have a severe effect on the plants even though the ozone concentrations were similar. While relative humidity was not measured during this study, an increased humidity associated with furrow irrigation is a possible cause of the increased plant sensitivity to ozone.

Unfortunately, all conclusions concerning humidity x air pollutant reactions to date have been based on experiments conducted in greenhouse studies. No field studies investigating humidity and air pollutants have been carried out. Thus, the predicted importance of humidity in crop sensitivity to pollutants has been approached with caution and has not been of great use for air quality management decisions.

A major factor for the lack of field studies of humidity x air pollutant interactions has been the lack of a humidification system suitable for open-top chambers or other field exposure systems. Field projects to date have concentrated on yield responses to different air pollutant concentrations, with essentially no effort being made to evaluate modifications in the exposure systems appropriate to controlling humidity.

Overall, the temporal and especially geographical differences in humidity make it difficult to predict the relative effects of specific air pollutant levels in California. It is also especially difficult to interpret the applicability of air pollutant effects in California if they are based on field research from areas of the United States with higher relative humidity levels than in California.

Statement of the Problem

No field studies have been conducted on humidity x air pollutant interactions despite scattered laboratory experimental data which indicated much greater pollutant injury to plants growing at high compared to low humidities. A major problem with these studies was the lack of a humidification system appropriate for field exposures using open-top chambers. A study was needed to specifically address field humidification system design prior to conducting major field humidity x air pollutant studies.

Objectives

Primary Objective. The primary objective of this study was to design and build a pilot humidification system compatible with open top field chambers and to determine the characteristics of the system under actual field exposure conditions. This objective was investigated using readily available humidification system components and several of the California Air Resources Board (CARB) open-top field chambers at the University of California, Riverside.

Subordinate Objectives

(1) Generate data relating humidification achieved with different target humidities, air flows and incoming air humidity.

(2) Conduct a pilot humidity x oxidant (ozone) interaction study of effects on two crops of alfalfa using two humidified chambers.

(3) Prepare a tentative plan for developing a test facility to humidify an adequate number of chambers to allow for precise testing of interactions between humidity levels and pollutants.

II. METHODS

A. Design of a Humidification System

Three methods of humidification of the atmosphere were considered; latent steam, pan evaporation of water and injection of a fine mist. Both of the latter were rejected. Evaporative pan humidification is suitable only for low capacity applications. It needs large areas, is subject to bacterial growth and has corrosion problems. It gives only one level of humidification at a given temperature.

Water spray humidification uses a fine mist that evaporates in an air stream. The heat of evaporation reduces the sensible heat of the air by approximately 1000 BTU's per pound of water evaporated. This would result in significant decreases in chamber air temperature compared to that of outside ambient air. Low temperatures and liquid water would again result in corrosion and maintenance problems.

Use of a boiler to produce steam was the most feasible of the three methods available for large scale humidification. Steam can result in rapid addition of large quantities of water vapor into air with little change in the air temperature. Because of the high temperatures required to produce only steam, the boiler remains sterile and unaffected by bacteria and has few corrosion problems because of a small amount of liquid water. This reduces the frequency and cost of system maintenance. Steam injection also has the advantage that a full range of relative humidities can be attained with the system in proportion to the steam injected via a modulating value into the air stream. The boiler is relatively inexpensive to operate as it uses propane as fuel. Boiler systems are readily available and are used for may industrial and institutional applications.

A number of propane fired boilers were evaluated and an AJAX (Ajax Boiler and Heater Co., Gardena, CA) was selected. This boiler, with a capacity for evaporating 450 kg (1000 lbs) of water per hour (1,000,000 BTU), was purchased and installed on a concrete slab near the instrument shelter and gas dispensing equipment which serves the California Air Resources Board Field Fumigation Facility. The concrete slab also served as a foundation for a sheet metal shelter for the boiler and ancillary

equipment. This allowed the use of two of the CARB facility open-top chambers and both the air monitoring instrumentation and pollutant generating equipment with essentially no modification of the existing facility.

B. Construction of a Humidification System

An Armstrong Humidifier (Guy Warden, Cerritos, CA) with controller was purchased to regulate the steam to the chambers ducting. The humidifier used a Honeywell potentiometer which senses and regulates the desired humidity level. A manual override of this controller was also installed to be used in startup trials and during short term experiments. For humidity monitoring, a dewpoint hygrometer system (Electro Mech Products, Inc., Milpitas, CA) was used. The system consisted of an analyzer, and 2 dewpoint sensors which were installed in the humidified and control chambers. A feed water deionizer, Simplex® condensate return system, and boiler feed pump were purchased and installed. To remove oxygen from boiler feed water and thus avoid corrosion of boiler tubes, a 5000 watt heater was installed in the 114 ℓ boiler feed tank. This kept the feed water at 80°C and allowed quicker startup. Large size (0.62 x 0.62m) galvanized steel ducting plus new plastic diffusers were constructed for injecting the humidity controlled air into the chambers. A concrete pad was poured and crash posts installed for the low pressure propane tank and pressure regulator. Tanks with ion exchange resin were obtained to provide low mineral feed water for the boiler.

Electric power was provided to the installed boiler and the ancillary equipment (Figure 1) and a sheet metal shelter was erected over the equipment. A barometric damper was provided to avoid blowout of the gas flame during windstorms. Insulated piping was provided to carry the low pressure 1.055 kg/cm^2 (15 PSI) steam to the galvanized ducting. New plastic was installed on the CARB chambers.

The initial tests of the boiler were supervised by an AJAX representative, Mr. John Fuller. The re-ignition system, low water cutoff, high and low steam pressure controls and humidifier controller worked satisfactorily. Residual metal filings, dirt and other contaminants were removed from the boiler by boiling out with soda ash and repeated blowdowns.

Figure 1. Steam boiler with boiler feed tank on right and overhead steam line on upper left to humidified chamber.

The air flow rates in chambers to be humidified (3 and 4) and the dry chambers (8 and 9), were checked and equalized by carbon monoxide (CO) dilution as a flow rate indicator. Carbon monoxide from a cylinder was metered into the blower boxes at a rate of 4.85 liters/min. An Ecolyzer® CO analyzer was used for monitoring flow. The CO concentration in the chamber was measured for approximately 10 minutes. The concentrations were as follows: chamber 3, 98 ppm; chamber 4, 71 ppm; chamber 8, 78 ppm and chamber 9, 86 ppm. thus showing appreciable differences in our flow rates. The corresponding flow rates were calculated according to the formula:

$$\text{Flow rate } (m^3/min) = \text{Incoming CO } (m^3/min)/\text{Chamber CO (ppm)}$$

By modifying the flow restrictors installed previously, the CO concentrations were corrected to 81, 80, 82 and 86 ppm for chambers 3, 4, 8 and 9. Applying the previous calculations, the flow rates proved to be essentially equal at 61.4 m^3/min, 60.6 m^3/min, 62.2 m^3/min and 60.6 m^3/min, respectively.

C. Ozone Addition

Ozone was added to one chamber during the acute exposure study. The ozone was generated by an Orec Inc. Ozonator, with tank oxygen to increase ozone production. Ozone was monitored with Dasibi® Model 1003 AN ultraviolet absorption analyzers, calibrated with a South Coast Air Quality Management District ozone transfer standard.

D. Plant Culture

The alfalfa (Medicago sativa) plants consists of three cultivars: "Mesa Sirsa" and "Moapa", which were ozone sensitive; and "Northrup King 286", which appears to be ozone resistant (3). The plants were propagated from single plants as clonal material (cuttings) in a mist bed. The clonal material was used to reduce plant-to-plant variability in ozone sensitivity within cultivars. This enhanced the potential for detecting humidity and ozone responses with the limited number of replicate plants per treatment.

The cuttings were transferred to 0.225 m diameter, 3.8 l pulp pots. The pots were placed in plastic liners in the ground in the open-top chambers. The soil mix consisted of 50% soil, 25% peat moss, and 25% redwood shavings. The alfalfa was fertilized with 1/100 strength North Carolina State University nutrient solution containing trace elements. Fertilization was via the irrigation water approximately every other day. Plants were sprayed with insecticides as needed. There were 10 plants of each cultivar for a total of 30 plants per chamber.

A limited number of bean plants (Phaseolus vulgaris) cultivar "Pinto" were grown in the chambers during the chronic injury studies. Plant culture was the same as for alfalfa.

E. Statistical Analysis

Statistical analysis of the plant study data was according to procedures described in Steel and Torrie (13). A two-way ANOVA was generally used with added humidity vs. ambient air as the two levels of the humidity factor, and filtered vs. ambient as the two levels of the air pollution factor. Individual plant data were the experimental units. An unpaired t-test was used to compare plant responses in humidified vs. ambient (dry) humidity chambers for the acute ozone exposure study. A paired t-test was used to compare stomatal conductance before vs. after addition of humidity for the same plants before the second harvest. All statistical significance was expressed at the $p<0.05$ level.

III. RESULTS AND DISCUSSION

A. Humidification Tests

Preliminary humidification tests showed that chambers receiving steam could have a relative humidity raised to only 57% with an outside humidity of 14% and ambient air temperature of 31.1°C (Table 2). This was lower than predicted. The fans had been predicted to deliver about 1.04 m^3 s^{-1} of air, however, upon measurement the air flow was much greater at 1.53 m s^{-1}. Reducing the chamber air flow to 1.06 m^3 s^{-1} increased the humidity to 74% in the chamber (Table 3). This humidity level was considered to be adequate for initiation of studies. All of the test relative humidity data presented in this report is for one chamber using one humidstat-controller. The single humidistat was the limiting factor for chamber humidification, the boiler has capacity to produce enough steam for at least six chambers with maximum potentiometer settings on the humidistats.

Because the air temperatures used in this study were somewhat lower than maximum air temperatures in the summer at Riverside, >40°C, a larger orifice is recommended for the humidifier-controller. The controller originally came equipped with a 0.0095 m diameter steam exit orifice which should be replaced with a 0.0127 m diameter orifice to allow for a 40% increase in steam emission. A larger orifice would provide much more steam for further tests. The larger replacement orifice was ordered for the original humidifier-controller, and the second humidifier-controller was ordered with the larger orifice already in place.

The inlet air was observed continuously for the presence of visible water droplets. This was carried out by placing a 0.46 m^2 square glass plate near the steam-air inlet into the chamber. No water droplets were observed under any air temperature or humidity conditions. Thus, the use of mist eliminators was not required to prevent liquid water from entering the chamber.

Sample results from further humidification tests using the reduced air flow rate are shown in Table 4. The data indicated that an increase of up to 60% in relative humidity can be obtained with a high potentiometer setting on the humidifier-controller, an air temperature of nearly 30°C and a low ambient relative humidity of 10%.

Table 2. Relative Humidity Levels with Different Potentiometer Setting and an Air Flow of 1.53 $m^3 s^{-1}$

Potentiometer Setting[a] (%)	Dewpoint (C)	Air Temp. (C)	Relative Humidity (%)
0	0.6	31.1	14
25	4.4	31.1	19
50	12.2	31.1	31
100	21.1	30.6	57

[a]The potentiometer is on the humidifier-controller.

Table 3. Relative Humidity Levels with Different Potentiometer Settings and an Air Flow of 1.06 $m^3 s^{-1}$

Potentiometer Setting* (%)	Dewpoint (C)	Air Temp. (C)	Relative Humidity (%)
0	1.1	26.7	19
100	23.6	27.2	83
0	1.4	30.6	13
100	23.9	30.0	70
0	0.6	28.3	15
100	23.3	28.3	74

*The potentiometer is on the humidifier-controller.

Table 4. Relative Humidity Levels with Different Potentiometer Settings on Two Days[a]

Potentiometer Setting[b] (%)	Day	Ambient "Dry" Chamber Dewpoint (C)	Ambient "Dry" Chamber Air Temp. (C)	Ambient "Dry" Chamber Relative Humidity (%)	Humidified Chamber Dewpoint (C)	Humidified Chamber Air Temp. (C)	Humidified Chamber Relative Humidity (%)
0	1	2.2	18.9	25	2.2	18.9	25
	2	-1.1	19.4	33	-1.1	19.4	33
30	1	2.2	18.9	33	2.2	18.9	33
40	1	-1.1	20.5	23	10.6	21.1	51
	2	1.1	26.7	19	12.2	26.7	41
50	1	-1.1	25.0	18	17.8	25.5	62
	2	1.1	28.3	17	18.9	28.9	55
60	2	-0.6	28.3	15	17.8	25.5	62
70	1	-4.4	29.4	11	22.2	29.4	65
	2	0	29.4	15	25.0	30.0	74
80	1	-5.6	29.4	10	23.3	29.4	70

[a]Values remained constant for at least one hour until an adjustment was made to the new potentiometer setting.
[b]The potentiometer is on the humidistat-controller.

B. Humidity and Ozone Depletion Tests

To prepare for an acute ozone x humidity study with alfalfa, tests were run to determine whether the addition of humidity would decrease the amount of ozone in the chamber. With an air temperature of 18.3°C and ambient humidity of 52%, a 25% increase in humidity resulted in a 56% decrease in the ozone level in the chamber (assuming a constant rate of ozone flow into the chamber). The data for two ozone depletion tests are shown in Table 5.

The ozone depletion problem can be overcome by addition of ozone to the humidified chamber to maintain the same air concentration as in the dry chamber. The causes for the ozone depletion with increased humidity could have been (a) condensation of water in the ozone sample line of the

Table 5. Ozone Reduction in Open-Top Chamber Due to Humidification

Ambient "Dry" Chamber				Humidified Chamber			
Dewpoint (C)	Air Temp. (C)	Relative Humidity (%)	Ozone (ppm)	Dewpoint (C)	Air Temp. (C)	Relative Humidity (%)	Ozone (ppm)
			Test I				
8.3	18.3	52	0.09	15.0	18.3	78	0.04
8.3	18.3	52	0.09	11.1	18.3	62	0.07
			Test II				
9.4	20.5	51	0.14	17.8	20.5	85	0.07
9.4	20.0	51	0.14	12.8	20.0	63	0.11

humidified chamber which would have resulted in less ozone reaching the analyzer, (b) sensitivity of the ozone analyzer to water vapor, and (c) real loss due to absorption into the water vapor in the chamber air. After extensive tests and discussions with SAPRC atmospheric chemists and the manufacturer of the ozone analyzer, it was determined that the problem was most likely caused by a real loss inside the chamber. The sample line length or a cooler location underground had no effect on the ozone depletion. The ozone analyzer was not believed to be sensitive to water vapor. One possibility was that the zinc and zinc oxide coating of the galvanized steel along the 24 m long ducting was catalyzing an ozone-to-oxygen conversion along the ducting walls. It is well known that the decomposition of ozone is very sensitive to heterogeneous catalysis by metals and metal oxides (1). The highly humidified air in duct may enhance this catalytic reaction. However, the entire question of ozone depletion with increased humidity was found to be an uninvestigated area which merits further study.

To investigate the problem further, small scale humidity x ozone concentration tests were conducted in a controlled environmental chamber. Reduced ozone concentrations were observed with increased humidity,

but the degree of ozone breakdown was not as great as in the field facility.

C. Acute Ozone Exposure Tests

For the acute ozone exposure tests 0.2 ppm ozone was added to one humidified and one ambient humidity "dry" chamber. Exposure of the alfalfa to both ozone and humidity was between 0900-1600 for two days. The ambient humidity in the dry chamber was less than 30%, and the humidity maintained at between 68 and 75% in the humidified chamber.

There were 30 plants of alfalfa in pots in each chamber. Injury was visible on the humidified plants by the end of the second day of exposure. Observations were made on 10 randomly selected plants (across all three cultivars), from each chamber two days after the exposures. More than 50% of the leaves were injured in the humidified chamber. Table 6 illustrates the average height, number of nodes, and number of empty nodes for 3 stems on each of the 10 plants. Height and total number of nodes were the same in both chambers, as expected from harvest soon after such a short exposure; i.e., there was not enough time for growth to be affected by the humidity treatment. However, the humidified chamber plants had much more defoliation compared to dry chamber plants, as measured by number of empty nodes. This increased defoliation was a good indication of the increased ozone injury in the humidified chamber plants.

Table 6. The Effects of Relative Humidity on Acute Injury from Ozone on Alfalfa Plants in the Field[a]

Parameter	Ambient "Dry" Chamber		Humidified Chamber
Height (m)	0.51 ± 0.06	ns	0.54 ± 0.05
Nodes/Stem (#)	9.0 ± 0.6	ns	9.5 ± 0.8
Leaf Injury (% Empty Nodes)	1.1 ± 1.3	*	5.5 ± 2.0

[a]Values are means ± SD for 10 plants, averaged for three stems/plant. The means for ambient vs. humidified chamber for % empty nodes were significantly different at $p<0.05$ using an unpaired t-test as indicated by "*".

D. Chronic Ozone Exposure Tests

Four chambers were used for the chronic ozone exposure tests: two humidified and two ambient humidity or "dry" chambers. One of each of the humidified and dry chambers received filtered air, and the other received ambient air. The air flows had to be adjusted between the humidified and dry chambers as the humidified chambers initially had lower air flow rates due to the longer duct. Exposure to ozone was between 0800-2000 PDT daily, and humidity between approximately 0900-1600 PDT, Monday-Friday. The ambient humidity in the dry chamber generally was less than 30%. The humidity was maintained at approximately 75%. Humidity generally oscillated between 68 and 82% in the humidified chamber except on windy days when humidity oscillated between 60 and 87%. Ozone levels during the period of exposure from March 21 to April 25, 1986 were relatively low for this time of year, rarely exceeding 0.10 ppm for one-hour averages. Twelve hour ozone averages for April 15 to June 22 from 0800 to 2000 o'clock were: ambient (outside) = 0.080, nonfiltered chambers = 0.066 and filtered chambers = 0.018 ppm.

For the first harvest on April 25, 1986, the dry weight and height per plant were determined, as well as number of leaves per stem and injured leaves per stem. More than 40% of the leaves were injured in the humidified, ambient air chamber. Table 7 illustrates the average weight, height, and percentage of injured leaves per treatment for Moapa, Mesa Sirsa, and NK 286. Humidifying the air increased overall plant growth, and made the plants more susceptible to air pollution injury. Chronic ozone injury was visible for humidified plants growing in ambient air. However, the ambient ozone had no effect on plant growth as expected due to the relatively low ozone concentrations during this period.

A second chronic injury study was initiated on April 26, with the plants harvested in mid-May. Injury was already evident in early May following a few days with ozone episodes as shown in Table 8. Leaf injury from ambient ozone was much more severe in the humidified compared to dry chambers. The resistant alfalfa cultivar, NK 286, had much less injury than Mesa Sirsa or Moapa.

Table 7. The Effects of Relative Humidity on Responses to Ozone of Alfalfa Plants in the Field at the First Harvest[a]

Parameter	Humidified Chamber		Dry Chamber	
	Filtered Air	Ambient Air	Filtered Air	Ambient Air
		Moapa		
Dry Weight ($g\ plant^{-1}$)	27.2 ± 6.3	24.3 ± 6.8	20.1 ± 5.1	20.2 ± 5.1
Height (m)	0.61 ± 0.06	0.59 ± 0.06	0.49 ± 0.09	0.53 ± 0.09
Leaf Injury (% empty nodes)	8.8 ± 4.9	43.2 ± 9.3	5.8 ± 6.0	13.0 ± 5.1
		Mesa Sirsa		
Dry Weight ($g\ plant^{-1}$)	27.2 ± 12.0	21.5 ± 5.3	20.9 ± 5.2	21.1 ± 6.3
Height (m)	0.64 ± 0.12	0.62 ± 0.08	0.55 ± 0.07	0.54 ± 0.04
Leaf Injury (% empty nodes)	8.1 ± 6.3	40.0 ± 6.3	7.4 ± 6.3	10.3 ± 5.5
		Northrup King 286		
Dry Weight ($g\ plant^{-1}$)	26.3 ± 5.5	24.6 ± 5.7	20.9 ± 8.2	21.1 ± 6.4
Height (m)	0.60 ± 0.09	0.62 ± 0.08	0.53 ± 0.09	0.61 ± 0.06
Leaf Injury (% empty nodes)	9.8 ± 7.1	34.9 ± 7.1	7.8 ± 6.3	9.0 ± 5.5

[a]Values are means ± SD for 10 plants, except for nine for Moapa in humidified and filtered air. Height and leaf injury measurements are based on one stem per plant. Statistically significant differences using ANOVA at $p<0.05$ occurred for all parameters and cultivars between humidified and dry chambers across filtered and ambient air treatments, except for Mesa Sirsa dry weight and NK 286 height. There was a significant difference for leaf injury between filtered and ambient chambers across humidified and dry air treatments, and a significant interaction between humidity and air.

Table 8. The Effects of Relative Humidity on Leaf Injury from Ozone Measured Before Second Harvest on May 7, 1986 to Alfalfa Plants in the Field[a]

Cultivar	Humidified Chamber		Dry Chamber	
	Filtered Air	Ambient Air	Filtered Air	Ambient Air
		(% Injured Leaves)		
Mesa Sirsa	5.8 ± 9.3	52.6 ± 10.9	9.5 ± 15.9	13.6 ± 6.8
Moapa	7.4 ± 10.0	63.8 ± 25.4	3.1 ± 6.6	4.2 ± 22.9
Northrup King 286	2.0 ± 6.3	14.1 ± 17.8	1.7 ± 5.3	8.2 ± 13.6

[a]Values are means ± SD for 10 plants, except for nine for Moapa-humidified and filtered air. For Mesa Sirsa and Moapa, statistically significant differences using ANOVA at $p<0.05$ occurred between humidified and dry chambers across filtered and ambient air treatments, between filtered and ambient air across humidified and dry chambers, and the interaction between humidity and air pollutant. For Northrup King 286 only the filtered vs ambient air comparison across humidified and dry chambers was statistically significant at $p<0.05$.

Stomatal conductance was measured to determine the physiological basis for the difference in leaf injury between treatments and cultivars. Conductance was determined with a LI-COR® 1600 steady-state porometer. Table 9 indicates the conductance on May 9, 1986, during a humidification and ozone exposure episode. Humidification produced a large increase in stomatal conductance for all cultivars. Thus, humidified plants had greater gas uptake and hence ozone dose to tissue inside leaves with the resulting increase in injury. There was some evidence for a decrease in conductance with ambient ozone, but only for Mesa Sirsa.

The effect of an abrupt change in humidity during the day on stomatal conductance was determined using alfalfa and beans on May 12, 1986 (Table 10). Conductance was increased greatly by humidity. For example, conductance was 117% higher for pinto beans in filtered air after, compared to before, humidification. The increase in conductance was very rapid, occurring within one hour after the extra humidity was added to the chamber.

Table 9. The Effects of Relative Humidity on Stomatal Conductance for Ozone Exposed Plants Measured Before the Second Harvest on May 7, 1986 to Alfalfa Plants in the Field[a]

Cultivar	Humidified Chamber		Dry Chamber	
	Filtered Air	Ambient Air	Filtered Air	Ambient Air
		($cm\ s^{-1}$)		
Mesa Sirsa	1.76 ± 0.26	1.50 ± 0.14	0.66 ± 0.09	0.54 ± 0.20
Moapa	1.42 ± 0.32	1.51 ± 0.29	0.81 ± 0.16	0.64 ± 0.19
Northrup King 286	1.73 ± 0.24	1.60 ± 0.14	1.19 ± 0.32	0.96 ± 0.22

[a]Values are means ± SD for five for replicate plants for Mesa Sirsa and Moapa, and four for Northrup King 286. For all cultivars, there are statistically significant differences using ANOVA at $p<0.05$ occurred between humidified and dry chambers across filtered and ambient air treatments. For Mesa Sirsa there was a statistically significant difference at $p<0.05$ between filtered and ambient air across humidified and dry chambers.

Table 10. The Immediate Effect of a Change in Relative Humidity on Stomatal Conductance for Plants Measured Before the Second Harvest on May 12, 1986 in the Field

Species	Humidity Status	Humidified Chamber	
		Filtered Air	Ambient Air
		($cm\ s^{-1}$)	
Mesa Sirsa Alfalfa	Before addition	0.86 ± 0.32	0.90 ± 0.33
	After addition	1.67 ± 0.36*	1.27 ± 0.29*
Pinto Bean	Before addition	0.66 ± 0.06	-
	After addition	1.43 ± 0.15*	-

[a]Values are means ± SD of eight plants for ambient-before and ambient-after for alfalfa, and five plants for filtered-before and filtered-after alfalfa and pinto beans. Pairs of before vs. after addition values followed by "*" are significantly different at $p<0.05$ level using a paired t-test.

At the second harvest, leaf injury from ozone was much greater in the humidified compared to dry chambers for Moapa and Mesa Sirsa, but not NK 286 (Table 11). Ambient ozone did not have any effect on plant growth or yield except for an ozone-associated increase in height for NK 286. Humidification did not result in increased growth or yield except for increased height for Moapa and NK 286, and increased fresh and dry weights for NK 286 compared to dry air.

A third chronic injury study with the three cultivars was begun May 16 and continued until harvest on June 13, 1986. As shown in Table 12, ozone by itself was associated with a reduced leaf dry weight for Moapa, total fresh and dry weights for Mesa Sirsa, and increased height for NK 286. Humidification was associated with an increase in height for Moapa and Mesa Sirsa, and % empty nodes for all cultivars. High humidity accentuated the ozone-associated reduction in fresh and dry weight for Moapa and % empty nodes for all cultivars. The increased defoliation may be especially significant with a forage crop, such as alfalfa, because the leaves contain much more nutrients per unit weight than the more woody stems.

E. Applicability of These Findings

This study indicated that humidification of field chambers is feasible with little other modification of the chamber environment. The only unanticipated environmental effect of long term humidification was a small but consistent temperature rise of 2.0-4.5°C in the humidified chambers compared to dry chambers (Table 13). The increase in temperature was due partly to the addition of the steam and due partially to the presence of the galvanized steel, steam-mixing manifold (7 in Figure 2). This difference occurred during the daylight hours and was greatest when outside temperatures were highest. The long mixing manifold became heated by solar radiation. As a result, the air was warmed 1.6-2.3°C as it moved through the hot manifold. Partially shading the manifold with 5.0 cm thick formed plastic failed to entirely overcome the heating effect. It is thought that covering the duct completely with thick fiberglass and foil insulation will prevent this minor temperature build up.

Table 11. The Effects of Relative Humidity on Responses to Ozone of Alfalfa Plants in the Field at the Second Harvest[a]

Parameter	Humidified Chamber		Dry Chamber	
	Filtered Air	Ambient Air	Filtered Air	Ambient Air
		Moapa		
Fresh Weight (g $plant^{-1}$)	132.7 ± 37.6	142.4 ± 67.7	117.3 ± 28.0	128.3 ± 33.4
Dry Weight (g $plant^{-1}$)	27.7 ± 8.0	27.6 ± 12.1	25.8 ± 6.9	27.1 ± 10.0
Height (m)	0.62 ± 0.07	0.66 ± 0.09	0.53 ± 0.06	0.57 ± 0.07
Leaf Injury (% empty nodes)	1.0 ± 3.3	54.4 ± 8.2	1.1 ± 3.5	18.6 ± 10.5
		Mesa Sirsa		
Fresh Weight (g $plant^{-1}$)	111.2 ± 42.5	86.6 ± 38.5	107.2 ± 21.7	104.0 ± 37.0
Dry Weight (g $plant^{-1}$)	23.4 ± 8.9	17.8 ± 7.5	23.5 ± 5.7	21.8 ± 7.4
Height (m)	0.60 ± 0.08	0.57 ± 0.05	0.58 ± 0.07	0.54 ± 0.04
Leaf Injury (% empty nodes)	2.9 ± 4.7	56.8 ± 8.5	6.4 ± 5.6	18.3 ± 16.2
		Northrup King 286		
Fresh Weight (g $plant^{-1}$)	90.6 ± 18.5	105.9 ± 30.0	71.5 ± 27.9	87.3 ± 24.5
Dry Weight (g $plant^{-1}$)	21.0 ± 3.7	32.8 ± 19.6	17.1 ± 6.2	18.8 ± 5.5
Height (m)	0.57 ± 0.05	0.62 ± 0.06	0.49 ± 0.09	0.60 ± 0.08
Leaf Injury (% empty nodes)	3.3 ± 5.4	38.6 ± 11.1	1.3 ± 4.0	29.3 ± 7.7

[a]Values are means ± SD for 10 plants, except for nine for Moapa in humidified and filtered air. Leaf injury measurements are based on three stems per plant. Statistically significant differences using ANOVA at $p<0.05$ occurred between humidity and dry chambers across filtered and ambient chambers for Moapa and NK 286 height, NK 286 fresh and dry weights, and for all three cultivars- % empty nodes. There was a significant difference between filtered and ambient chambers across humidity treatments for NK 286 height, and for all three cultivars- % empty nodes. There was a significant interaction between humidity and air for all Moapa and Mesa Sirsa for % empty nodes.

Table 12. The Effects of Relative Humidity on Responses to Ozone of Alfalfa Plants in the Field at the Third Harvest[a]

Parameter	Humidified Chamber		Dry Chamber	
	Filtered Air	Ambient Air	Filtered Air	Ambient Air
		Moapa		
Fresh Weight ($g\ plant^{-1}$)	108.7 ± 45.7	73.4 ± 19.1	89.1 ± 8.4	94.2 ± 16.7
Dry Weight ($g\ plant^{-1}$)	30.6 ± 10.2	20.5 ± 5.4	26.2 ± 1.6	27.1 ± 5.4
Leaf Dry Wt. ($g\ plant^{1}$)	15.0 ± 4.3	8.6 ± 2.8	13.2 ± 1.6	12.2 ± 3.0
Height (m)	0.65 ± 0.10	0.60 ± 0.05	0.54 ± 0.07	0.61 ± 0.07
Leaf Injury (% empty nodes)	1.3 ± 5.2	71.3 ± 10.3	3.6 ± 4.6	37.5 ± 7.1
		Mesa Sirsa		
Fresh Weight ($g\ plant^{-1}$)	87.8 ± 16.3	71.3 ± 16.6	81.4 ± 14.5	77.3 ± 14.7
Dry Weight ($g\ plant^{-1}$)	24.6 ± 4.6	20.0 ± 5.8	23.9 ± 4.2	21.6 ± 3.5
Leaf Dry Wt. ($g\ plant^{-1}$)	10.8 ± 2.5	9.2 ± 2.1	11.2 ± 1.6	10.4 ± 2.0
Height (m)	0.61 ± 0.07	0.64 ± 0.06	0.54 ± 0.12	0.55 ± 0.07
Leaf Injury (% empty nodes)	3.7 ± 4.7	71.8 ± 7.1	2.6 ± 4.4	46.1 ± 7.9
		Northrup King 286		
Fresh Weight ($g\ plant^{-1}$)	79.3 ± 17.5	68.1 ± 10.1	68.9 ± 17.4	68.0 ± 13.7
Dry Weight ($g\ plant^{-1}$)	20.5 ± 4.4	18.0 ± 2.9	19.0 ± 5.0	17.7 ± 3.3
Leaf Dry Wt.[b] ($g\ plant^{-1}$)	---	---	---	---
Height (m)	0.55 ± 0.05	0.59 ± 0.05	0.51 ± 0.08	0.58 ± 0.06
Leaf Injury (% empty nodes)	1.6 ± 4.2	58.0 ± 5.8	0.7 ± 2.9	40.7 ± 7.0

[a]Values are means ± SD for 10 plants, except for nine for Moapa in humidified and filtered air. Leaf injury measurements are based on three stems per plant. Statistically significant differences using ANOVA at $p<0.05$ occurred for between humidified and dry chambers across filtered and ambient air treatments for Moapa and Mesa Sirsa height, and all cultivars % empty nodes. There was a significant difference between filtered and ambient air treatments across humidified and dry chambers for Moapa leaf dry weight, Mesa Sirsa fresh and dry weights, Northrup King 286 height, and all cultivars % empty nodes. There was a significant interaction between humidity and air for Moapa fresh weight, dry weight, and height; and all cultivars % empty nodes.

[b]Not measured.

Table 13. Temperature Increase Between Dry and Humidified Chambers

Time	Dry Chamber (^oC)	Δ^oC	Humidified Chamber (^oC)	Comments
		5/7/86		
1600	25.0	1.6	26.6	Steam off
1700	22.2	0.6	22.8	
1800	18.9	0.5	19.4	
1900	15.5	0.6	16.1	
2000	13.9	0.5	14.4	
2100	13.3	0.6	13.9	
2200	12.8	0.5	13.3	
2300	12.8	0	17.8	
2400	11.7	0	11.7	
		5/8/86		
0100	10.0	0	10.0	
0200	9.4	0	9.4	
0300	8.3	0	8.3	
0400	8.3	0	8.3	
0500	7.8	0	7.8	
0600	12.2	1.1	13.3	
0700	16.7	0.6	17.3	
0800	19.4	1.1	20.5	
0900	23.3	0.6	23.9	
1000	25.5	2.3	27.8	
1100	28.3	2.2	30.5	
1200	29.4	4.5	33.9	Steam on
1300	30.5	2.3	32.8	Steam off & shade
1400	30.5	2.3	32.8	Steam off & shade
1500	29.4	2.8	32.2	Steam off & shade off
1600	29.4	3.9	33.3	Steam on
1700	27.2	3.9	31.1	Steam off
1800	22.8	1.1	23.9	Steam off
1900	18.9	0.5	19.4	
		5/12/86		
0700	14.4	1.1	15.5	
0800	15.5	2.3	17.2	
0900	17.8	1.1	18.9	
1000	22.2	1.1	23.3	
1100	25.0	1.6	26.6	
1200	26.1	2.2	28.3	
1300	27.2	2.8	30.0	
1400	28.3	1.7	30.0	Steam on
1500	28.9	3.9	32.8	Steam on
1600	28.3	4.5	32.8	Steam off
1700	30.0	1.7	28.3	Steam off
1800	24.4	1.7	26.1	
1900	22.2	1.1	23.3	

Continued

Table 13. (Continued)

Time	Dry Chamber (°C)	Δ (°C)	Humidified Chamber (°C)	Comments
		5/16/86		
0700	16.7	0.5	17.2	
0800	17.2	0.6	17.8	
0900	18.3	0.6	18.9	
1000	20.0	0.5	20.5	
1100	23.9	1.1	25.0	
1200	26.1	2.2	28.3	
1300	27.8	2.2	30.0	Steam on
1400	28.9	3.9	32.8	Steam on
1500	29.4	3.9	33.3	
1600	28.9	3.9	32.8	Steam off
1700	28.3	1.1	29.4	Steam off
1800	25.5	1.7	27.2	

Theoretically, if the steam is allowed to come to ambient temperature and pressure little increase in air temperature with the "steam on" should have occurred. However because the vapor is at 100°C, when mixed with the air it causes the small temperature rise of an extra 2°C (Table 13). This temperature differential between the two atmospheres is much less than could be obtained if some evaporative type of humidification was used because of the large amount of heat needed to evaporate water and the consequent cooling of the air stream.

Considerable effort was made to determine how the humidification system could be automatically controlled via a computer system. The available dewpoint sensors required concurrent air temperature measurements for calculation of relative humidity. Thus, it was difficult to provide a single signal to a computer, and then send a signal from a computer back to the humidistat controller. A computer program was developed for the first aspect of control; i.e. to simultaneously monitor the dewpoint and air temperature signals and to record the data on disk. This program currently is being used to collect data at the ARB field site.

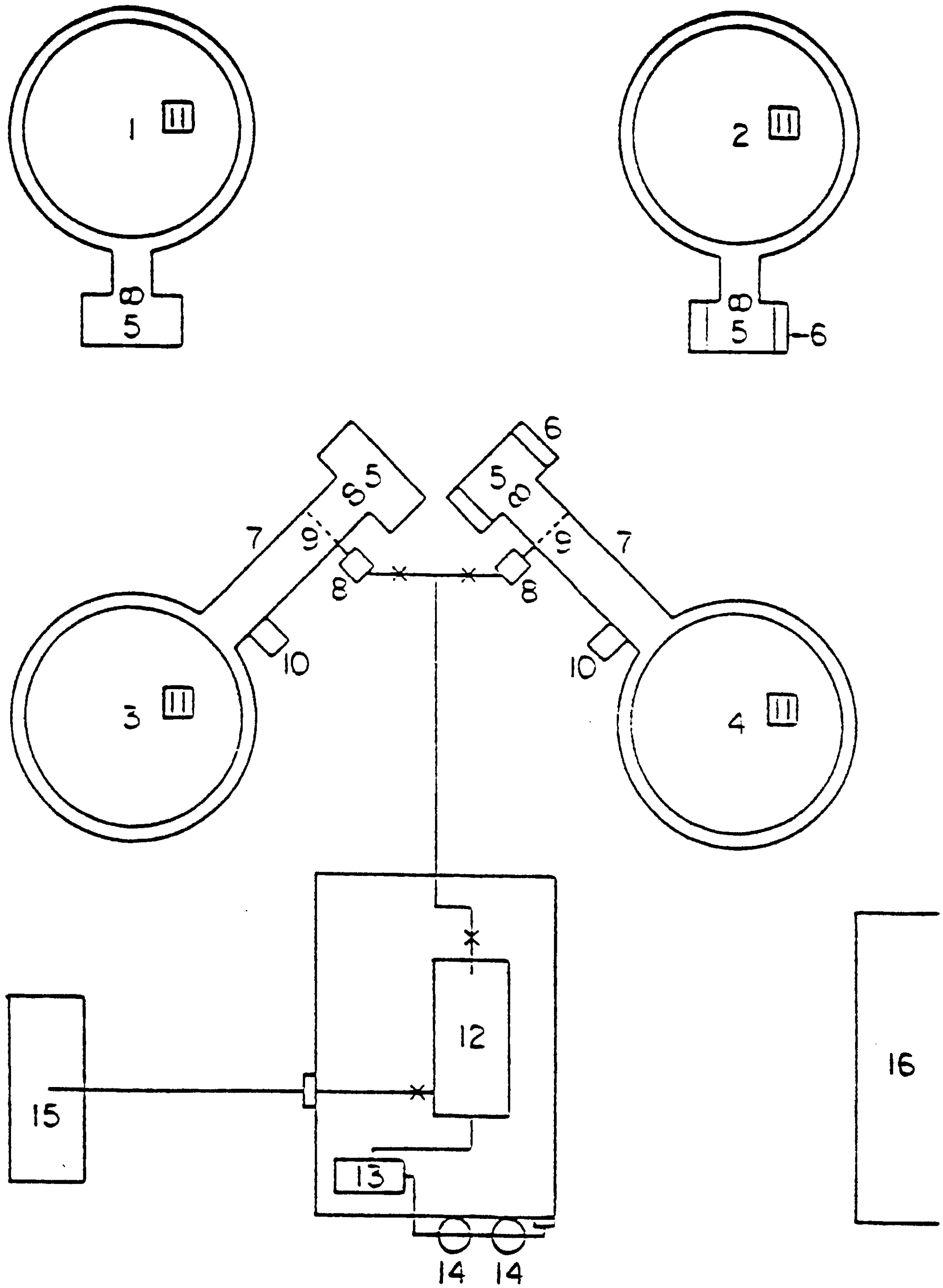

Figure 2. Humidification system components are: 1 - open-top chamber #8 dry ambient, 2 - open-top chamber #9 dry filtered, 3 - open-top chamber #3 humidified ambient, 4 - open-top chamber #4 humidified filtered, 5 - blowerbox with 3/4 Hp blower, 6 - charcoal filter, 7 - galvanized duct for humidification supply, 8 - modulating value + steam separator, 9 - steam manifold, 10 - humidistat, 11 - temperature and humidity sensors, 12 - steam-boiler, 13 - boilerfeed pump, 14 - water softeners, 15 - propane tank, and 16 - instrument building.

Aspects of a computer program are being evaluated to take the calculated humidity levels, compare them to a target humidity, and to send a signal to the controller.

A computer-controlled humidification may not be required for actual field studies. The original intent of computer control was to help maintain a set humidity with variable ambient conditions, and to change the humidity rate over time to mimic ambient conditions. Neither of these control patterns are required for studies designed to test effects of increased humidity on plants at Riverside.

Relative humidity levels were surprisingly uniform over the day once early morning cloud cover had "burned" off. Manual setting of the controller at a specific humidity resulted in a constant humidity at that level during the day. The desired humidity level was attained within 20 minutes after the steam was turned on. Only slight adjustments were required to increase humidity with increasing temperatures in the afternoon. This uniformity of humidification over the day is associated with the consistent low humidity over the day. Because a large amount of steam was already required to raise the humidity in the chamber to 60 or 70% RH at the start of the day, small fluctuation is ambient humidity had little effect on the overall chamber humidity level. In addition, because ambient relative humidity levels are constant over the day, computer control is not required to "mimic" natural fluctuations in humidity.

Thus, continued manual control of humidity is recommended for any future simple humidity addition studies at Riverside. Personnel are generally present at the site at all times during humidification study to observe the boiler and take measurements on plants. The individuals could easily make small changes in humidity in the chambers. However, development of computer controls will continue for maximum flexibility of the humidification system to modify chamber humidity levels.

These studies show that plants are much more sensitive to ozone at higher relative humidity partly because the stomates are open wider and thus allow more air pollutant exchange. Unknown biochemical effects may also be involved. Because of this greater sensitivity in areas of higher humidity it should be possible to predict losses with crops and injury to ornamentals and forest species more accurately if information is obtained which shows how much loss occurs with a given air pollutant level and a

particular level of ambient humidity. Thus, economic losses caused by air pollutants can be better assessed for a given region and air quality standards for protection of vegetation by regulatory agencies can be set with greater reliability.

Future studies with a variety of different crops should be conducted to quantify the relationship between increased relative humidity and changes in ozone dose-crop yield equations. A tentative experimental design for future humidity x air pollutant interaction studies would include four additional humidified chambers. This would allow for replication of specific humidity and air pollutant treatments. A total of six humidified chambers along with six nonhumidified chambers would allow for a study with either two humidity levels (added and ambient) and two air pollutant levels to be replicated in three chambers, or three humidity levels (added medium humidity, added high humidity, and ambient) and two air pollutant levels to be replicated in two chambers.

The existing boiler has enough capacity to supply four additional chambers with steam, assuming an ambient air temperature of 30°C and relative humidity of 20% (see Appendix). The expanded humidification system would require four new sets of equipment for each chamber including: elongated galvanized duct, modulating value and steam separator, steam manifold, humidistat, and humidity sensors. Humidity sensors also would be required for the four additional nonhumidified chambers.

Any future humidity study should emphasize the physiological bases for increased air pollutant sensitivity with increased relative humidity, in addition to growth and yield measurements. In particular, stomatal conductance was shown to be very sensitive to relative humidity levels. The increased stomatal conductance with increased humidity provides a direct mechanism for increased air pollutant uptake into plants, with subsequent phototoxic effects.

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APPENDIX

TARGET HUMIDITY LEVELS AND EQUIPMENT REQUIRED TO HUMIDIFY ADDITIONAL CHAMBERS

During the pilot project described in this report, the humidification system was used to add humidity to two chambers. There was no problem in providing steam to increase the relative humidity from about 20 to 70% at an air temperature of 30°C for the two chambers. Even under the driest ambient conditions the second half of the boiler heater was never lit, indicating that the boiler never approached one-half of its capacity. It was not possible to empirically determine how much steam actually was emitted by the boiler for the two chambers vs. its total capacity. However, the boiler was purchased because of its rated capacity (500 kg steam/hour) and the number of chambers supplied and incremental addition of humidity to those chambers could be calculated based on that capacity.

Table A-1 indicates the theoretically number of chambers that could be supplied from the existing boiler with different air temperatures and a target humidity levels. A low ambient humidity of 20% and high air temperatures were used in the calculations as they represent possible conditions in Riverside during the summer. The cost of additional equipment for those chambers also is given. It must be remembered that these numbers were determined for a specific set of conditions and would differ with other ambient air temperatures and humidities, however air temperatures and higher humidities would result in more chambers being equipped and potentially greater additions of humidity to those chambers. Higher air temperatures and lower humidities would result in fewer chambers being humidified and less humidity added to each chamber. The calculated values also assumed that all humidified chamber would receive the same maximum humidification. If an experiment used a gradient of humidity levels, than more chambers could receive lower humidities.

The calculations were based on tables of water content in air supplied by the boiler manufacturer and by standard environmental data references. The needed steam was calculated as:

$$\left(\begin{array}{c}\text{Water in Steam} \\ \text{at Air T and} \\ \text{Desired RH} \\ (\text{kg m}^{-3})\end{array} - \begin{array}{c}\text{Water in Steam} \\ \text{at Air T and} \\ \text{Ambient RH} \\ (\text{kg m}^{-3})\end{array}\right) \times \begin{array}{c}\text{Air Flow} \\ \text{Through} \\ \text{Chamber} \\ (1.35 \times 10^5 \text{ m}^3 \text{ hr}^{-1})\end{array} = \begin{array}{c}\text{Needed} \\ \text{Steam} \\ (\text{kg hr}^{-1})\end{array}$$

The total chambers that could be supplied was calculated as boiler capacity (500 kg hr^{-1})/needed steam. The additional equipment was determined based on approximate costs for existing equipment for two chambers.

Table A-1. Additional Equipment Required to Humidify Additional Chambers at Different Air Temperatures and Target Humidities

Air Temperature (°C)	Target Humidity[a] (%)	Needed Steam[b] (kg hr^{-1})	Total Chambers Supplied[c] (#)	Additional Equipment[d] Chambers (#)	Additional Equipment[d] Cost[e] (Total $)
40	50	39	11	9	18,900
	70	98	4	2	4,200
35	50	30	15	13	27,300
	70	76	5	3	6,300
30	50	23	19	17	35,000
	70	58	7	5	110,500
25	50	18	25	23	48,300
	70	44	10	8	16,800

[a] Increase from an ambient humidify of 20%.
[b] From the existing single boiler with 500 kg hr^{-1} capacity.
[c] For one chamber.
[d] In addition to two existing humidified chambers.
[e] For humidifier ($1,500), humidity sensor and electronic ($150), expanded blower box ($200), and miscellaneous piping etc. ($250); total of $2,100 per chamber.

It was assumed that the additional humidified chambers would be part of the existing 20 chamber CARB maintained facility at UCR. Thus there would in actuality be only 20 chambers for both humidified and non-humidified control treatments. All of the calculations are based on use of the existing boiler. Purchase and installation of a second boiler would double the potential existing chambers, but in excess of the approximately $6,000 needed for the initial boiler.

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A humidity generation system was designed, constructed, and tested to increase relative humidity (RH) within open top field chambers under field conditions. The system consisted of a gas fired steam boiler capable of generating 450 kg of steam at 1.055 kg/cm^2 pressure. A modulating valve, controlled by a humidity sensor, metered steam to the chambers. At air temperatures of 30 degrees C and ambient RH of 10%, the RH of the chambers could be increased by 60%. At higher ambient humidities, a greater maximum chamber humidity was achieved. Alfalfa plants exposed to 0.20 ppm of ozone at high RH 7 hrs/day for 2 days had visible injury to more than 50% of the leaves and increased leaf crop. Chronic exposure of alfalfa to ambient ozone at elevated RH over three harvest periods, resulted in 40% visible injury in the first and second harvests, and increased stomatal conductance. At the third harvest, exposure to ozone with elevated RH reduced dry weight and increased defoliation.

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